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Xiang-Gen Xia

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Department of Electrical and Computer Engineering
University of Delaware
Newark, DE 19716

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14. ABSTRACT

This report describes the main research achievements during the time period cited above on the research project in the area of wireless communications. The main achievements include new space-time/frequency code designs based on algebraic number theory, new space-time code designs with a new design criterion that achieve full spatial diversity when linear receivers such as MMSE and ZF receivers are used, and algebraic space-time code designs that achieve the full cooperative diversity in cooperative communications systems when synchronization between relay nodes does not hold, and also space-time codes for cooperative systems that are robust to both timing errors and frequency offsets.

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Submitted By:

Xiang-Gen Xia
Department of Electrical and Computer Engineering
University of Delaware
Newark, DE 19716
Phone/Fax: (302)831-8038/4316
Email: xxia@ee.udel.edu

A. **Objective**: The goal of this research is to design new, systematic and optimal space-time, space-frequency, and space-time-frequency codes based on lattices over cyclotomic and quadratic fields using algebraic number theory, and investigate their properties and applications in broadband wireless communications.

B. **Main Research Accomplishments**: We have made several research accomplishments as follows.

(I) New Space-Time/Frequency Block Coding for MIMO Systems

(i) *New Constructions of Nonvanishing Determinant Space-Time Block Codes Based on Cyclic Division Algebra*: It is known that to construct an $n \times n$ full rate space-time block code (STBC) with nonvanishing determinant (NVD) based on cyclic division algebra (CDA) usually consists of two steps. The first step is to construct a degree-n cyclic Galois extension over a base field and the second step is to find a non-norm algebraic integer in the base field. The basic idea of the existing methods for the first step is first to factorize n into a product of powers of primes, p^m, and then construct degree-p^m cyclic Galois extensions and the final one is the composition of these degree-p^m cyclic Galois extensions. We call this approach as down-to-up method. We have proposed a different and new approach called up-to-down method by using the Kronecker-Weber Theorem that implies that any cyclic Galois extension K over Q is a subfield of some cyclotomic field.We start with a larger cyclotomic field and then construct degree n Galois extension K over Q and finally add i to K properly to make it a cyclic Galois extension over $Q(i)$. For the second step, based on Kiran-Rajan's sufficient condition we have also proposed some new sufficient conditions for non-norm elements γ so that new non-norm elements γ have smaller absolute values for our newly proposed cyclic Galois extensions in the first step than the existing ones, which may lead to new STBC with smaller mean signal powers while their minimum non-zero determinant absolute values (also called diversity products) are all 1.

We have obtained a transformation technique to improve the normalized diversity product for a full rate algebraic space-time block code (STBC) by balancing the signal mean powers at different transmit antennas. After rewriting a cyclic division algebra structure into a multi-layer structure for a full rate code, we have shown that the normalized diversity product of the transformed code with the multi-layer structure is better than the one of the transformed code with the cyclic division algebra structure. We have then obtained a new full rate algebraic STBC with multi-layer structure with non-vanishing determinant (NVD) for three transmit antennas when signal constellation is carved from QAM. We have shown that the new code has larger normalized diversity product than the existing 3×3 NVD full rate STBC for QAM signals, and we have also shown that it has the largest normalized diversity product in a family of full rate STBC.

(ii) *New Criterion and Constructions of Space-Time Block Codes Achieving Full Diversity with Linear Receivers*: In most of the existing space-time code designs, achieving full diversity is based on maximum-likelihood (ML) decoding at the receiver that is usually computationally expensive and may not have soft outputs. In this work, we proposed a design criterion for space-time block codes (STBC), in which information symbols and their complex conjugates are linearly embedded, to achieve full diversity when ZF or MMSE receiver is used. We showed that general (complex) orthogonal STBC (OSTBC) indeed satisfy the criterion as one may expect. We also showed that the symbol rate can not be above 1. We then proposed a novel family of STBC that also satisfy the criterion and thus achieve full diversity with ZF or MMSE receiver. Our newly proposed STBC are constructed by overlapping the 2×2 Alamouti code and hence named *overlapped Alamouti codes*. The new codes are close to orthogonal while their symbol rates can approach 1 for any number of transmit antennas, i.e., their rates are asymptotically optimal. Our simulation results showed that overlapped Alamouti codes significantly outperform the existing Toeplitz codes for all numbers of transmit antennas and also outperform OSTBC when the number of transmit antennas is above 4.

(iii) *Optimal Normalized Diversity Product of 2×2 Lattice Based Diagonal Space-Time Codes from QAM Signal Constellations:* In this work, we have proved that the optimal normalized diversity product of 2×2 lattice based diagonal space time block codes with Gaussian integer (or QAM) signal constellations, i.e., $\mathbb{Z}[\mathbf{i}]$, and any generating matrices of complex entries (not necessarily algebraic extensions of $\mathbb{Z}[\mathbf{i}]$ as commonly used) is $1/\sqrt{3}$. This result implies that 2×2 lattice based diagonal space time block codes with Gaussian integer signal constellations and generating matrices of entries from quadratic algebraic extensions of $\mathbb{Z}[\mathbf{i}]$ have already reached the optimal normalized diversity product.

(iv) *High-Rate Full-Diversity Algebraic Space-Time-Frequency Codes for Broadband MIMO Block-Fading Channels:* We have proposed a systematic design of rate-M_t full-diversity space-time-frequency (STF) code for MIMO frequency-selective block-fading channels. We showed that the codes from this design achieve the full-diversity

$M_t M_r M_b L$, i.e., the product of number of transmit antennas, receiver antennas, fading blocks and channel taps. The proposed STF codes are constructed from a layered algebraic design, where each layer of algebraic coded symbols are parsed into different transmit antennas, OFDM tones and fading blocks without any rate loss. The performance of some existing SF codes and the proposed STF codes were simulated and compared.

(v) *General Orthogonal Space-Time Block Codes for MIMO-OFDM Systems with Full-Diversity and Fast ML Decoding Properties:* Orthogonal space-time block codes (OSTBC) facilitate a simple transmit diversity technique with full-diversity and a fast maximum-likelihood (ML) detection in flat fading channels. We have proposed a general OSTBC to MIMO-OFDM system over frequency-selective fading channels and aim to exploit the potential multipath diversity. By stacking the repeated symbols as entries of an OSTBC matrix, the full-diversity property of an OSTBC is still satisfied in frequency-selective fading channels. Moreover, the ML decoding complexity can be performed separately on each symbol, i.e., single-symbol decoding. Given the information of channel power delay profile at transmitter, the diversity product of the proposed STBC can be further optimized through OFDM subcarrier permutation. Simulation results are presented to show that the STBC can achieve a full-diversity performance in frequency-selective fading channels with a fast ML decoding. Focusing on two transmit antennas, the proposed STBC can achieve a higher diversity gain than Alamouti code but still have a single-symbol decoding complexity.

(vi) *Fast ML Decoding for Orthogonal and Quasi-Orthogonal STBC in Clipped MIMO-OFDM Systems Using A Clipping Noise Model:* MIMO-OFDM systems have been commonly recognized as future broadband wireless systems and have been adopted in current IEEE standards, such as WiFi 802.11n and WiMax 802.16e. An important issue for OFDM systems is its peak-to-average power ratio (PAPR) and an efficient way to reduce the PAPR in OFDM systems is clipping. After the clipping in an MIMO-OFDM system, the additive noise may not be white. In this work, we have obtained fast ML decoding algorithms for orthogonal space-time block codes (OSTBC) and quasi orthogonal space-time block codes (QOSTBC) in clipped MIMO-OFDM systems by taking the clipping noise into the account and using a clipping noise model. By using the statistics of the clipping distortions, our newly proposed fast ML decoding algorithms improve the performance for clipped MIMO-OFDM systems with OSTBC and QOSTBC without increasing the decoding complexity. Simulation results are presented to illustrate the theory.

(vii) *Peak-to-Average Power Ratio (PAPR) Reduction for Space-Time-Frequency Coded MIMO-OFDM System*: Space-time/frequency coding (SFC) can achieve the spatial and multipath diversities for a MIMO-OFDM system by coding across subcarriers, multiple antennas, and/or multiple OFDM sysmbols, where an interesting method to achieve the multipath diversity is repeating across subcarriers proposed by Su et al. While most of the existing space-time/frequency codes do not have the fast ML decoding, a family of space-time-frequency codes with single-symbol ML decoding have been proposed lately by Zhang et al to achieve both full spatial and multipath diversities by using orthogonal space-time block codes (OSTBC) across multiple antennas and OFDM symbols and in the meantime repeating across the subcarriers. In this work, we first generalized the above OSTBC to linearly transformed quasi OSTBC (QOSTBC) in a straightforward way. The main goal of this work was to modify the repeating process and adjust their phases so that the peak-to-average power ratio (PAPR) of the OFDM system is reduced. In particular, we proposed to use Chu sequences and show that the discrete PAPR can be reduced by Γ times where Γ is the times of the repeating across subcarriers for any SFC from the repeating.

(II) New Space-Time/Frequency Coding for Cooperative Systems

(i) *Shift Full Rank Matrices and Applications in Space-Time Trellis Codes for Relay Networks with Asynchronous Cooperative Diversity:* To achieve full cooperative diversity in a relay network, most of the existing space-time coding schemes require the synchronization between terminals. A family of space-time trellis codes that achieve full cooperative diversity order without the need of the synchronization has been recently proposed by the PI in the previous AFOSR supported project. The family is based on the stack construction by Hammons and El Gamal and its generalizations by Lu and Kumar. It has been shown that the construction of such a family is equivalent to the construction of binary matrices that have full rank no matter the shifts of their row vectors, where a row corresponds to a terminal (or transmit antenna) and the length of a row vector is the memory size of the corresponding trellis code on the corresponding terminal. We call such matrices as shift full rank (SFR) matrices. A family of SFR matrices has been also constructed but the memory sizes of the corresponding space-time trellis codes (the number of columns of SFR matrices) grow exponentially in terms of the number of terminals (the number of rows), which may cause a high decoding complexity when the number of terminals is not small. In this work, we have systematically studied and constructed SFR matrices of any sizes for any number of terminals. Furthermore, we have constructed shortest (square) SFR matrices that correspond to space-time trellis codes of smallest memory sizes with asynchronous full cooperative diversity.

To produce more eligible SFR matrices with larger weights, We have studied two variations of SFR matrices with relaxed conditions: 1) SFR matrices with step delay, i.e., matrices having full rank when the shifts of their rows are multiples of some preassigned constants, 2) SFR matrices with delay tolerance, i.e., matrices having full rank when their rows are shifted in some range called delay tolerance. We have obtained systematic constructions for these two variant SFR matrices. We have also constructed some space-time block codes with asynchronous cooperative full diversity by studying an equivalent condition for matrix construction.

(ii) *A Distributed Linear Convolutive Space-Time Codes*: In user cooperative communications, time asynchronism among the relay nodes may distort the structure of a distributed space-time code, and therefore impair the diversity gain. In this work, a distributed linear convolutive space-time coding scheme was proposed for asynchronous cooperative communication networks. We proposed systematic construction methods of linear convolutive space-time codes (DLC-STC) that are insensitive to the timing errors, i.e., they achieve the full spatial diversity under any delay profiles. We then proposed minimum mean square error decision feedback equalizer (MMSE-DFE) receiver for our newly proposed codes, which has a low decoding complexity. We showed that with the MMSE-DFE receiver, our proposed codes also achieve the full spatial diversity in the asynchronous scenario, which is then confirmed by our simulation results.

(iii) *Distributed Space-Time Block Coding in Asynchronous Wireless Relay Networks*: Jing and Hassibi recently presented a detailed analysis on the problem of distributed space-time coding for a synchronized wireless relay network, where only linear transforms are implemented at relay nodes, and proposed a linear dispersion coding scheme. In this work, we extended it to asynchronous wireless networks by employing OFDM to combat timing errors from relay nodes. Based on a layered structure, we present a distributed space-time code design achieving full spatial diversity for an asynchronous wireless relay network.

(iv) *An Alamouti Space-Time Transmission Scheme for Asynchronous Cooperative Systems*: In this work, we proposed an orthogonal frequency-division multiplexing (OFDM) scheme for an asynchronous cooperative system where OFDM is implemented at the source node and time-reversion and complex conjugation are implemented at the relay nodes. The cyclic prefix (CP) at the source node is used for combating the timing errors from the relay nodes. In this scheme, the received signals at the destination node have the Alamouti code structure on each subcarrier and thus it has the fast symbol-wise ML decoding. It should be emphasized that the relay nodes only need to implement the time-reversion, some sign changes from plus to minus, and/or the complex conjugation to the received signals, and no IDFT or DFT operation is needed. It was shown that this simple scheme achieves second-order diversity gain without the synchronization requirement at the relay nodes.

(v) *An Alamouti Coded OFDM Transmission for Cooperative Systems Robust to Both Timing Errors and Frequency Offsets*: In this work, we obtained an Alamouti coded orthogonal frequency-division multiplexing (OFDM) scheme for a cooperative communication system robust to both timing errors and frequency offsets. OFDM with cyclic prefix (CP) is used to combat timing errors. In order to mitigate the intercarrier interference (ICI) caused by multiple freq uency offsets in the cooperative system, an ICI-self cancellation scheme was constructed, which can suppress ICI effectively. Moreover, in the proposed scheme, if the channels are real-valued fading channels, the received signals at the destination node have the Alamouti code structure on each subcarrier and thus it has the fast symbol-wise ML decoding and when frequency offsets are not large, the new scheme can achieve diversity order 2.

(III) Robust Phase Unwrapping, Chinese Remainder Theorem, and Their Applications in SAR Imaging of Moving Targets

(i) *A Sharpened Dynamic Range of a Generalized Chinese Remainder Theorem for Multiple Integers:* A generalized Chinese Remainder Theorem (CRT) for multiple integers from residue sets has been proposed recently by the PI. In this work, we first proposed a majority method and then based on the proposed majority method we obtained a sharpened dynamic range of multiple integers that can be uniquely determined from their residue sets.

(ii) *A New Robust Phase Unwrapping Algorithm and A Robust Chinese Remainder Theorem:* In the conventional Chinese Remainder Theorem (CRT), a small error in a remainder may cause a large error in the solution of an integer, i.e., CRT is not robust. In this work, we have obtained a robust phase unwrapping algorithm with applications in radar signal processing. Motivated from the phase unwrapping algorithm, we have then obtained a robust CRT.

(iii) *New SAR Techniques for Fast and Slowly Moving Target Imaging and Location:* We have obtained non-uniform antenna array synthetic aperture radar (NUAA-SAR) where an antenna array is arranged into a few subgroups. We have shown that NUAA-SAR can image and accurately locate both slowly and fast moving targets. We have also obtained non-uniform speed antenna array SAR that can also image and accurately locate both slowly and fast moving targets.

(iv) *Fast Implementation of A New Robust Phase Unwrapping Algorithm and A Robust Chinese Remainder Theorem:* In the last year, we proposed a robust phase unwrapping algorithm and a robust Chinese remainder theorem (CRT) where the algorithm is based on a two dimensional (2-D) searching. In this work, we obtained an efficient implementation of the robust phase unwrapping algorithm. We showed that the range of the 2-D searching, and therefore the complexity of the robust phase unwrapping algorithm and CRT, can be significantly reduced. We further reduced it into a one-dimensional searching.

C. Significance:

High rate full diversity linear lattice based space-time codes can achieve the optimal diversity-multiplexing trade-off and in the meantime have fast decoding algorithms. Their optimal constructions for MIMO and MIMO-OFDM systems may significantly improve the throughput of broadband wireless systems. The results we have obtained in this research may have profound impact in space-time, space-frequency, and space-time-frequency coding for MIMO and MIMO-OFDM systems that may be applied to broadband wireless communication systems.

One of the main difficulties in utlizing the existing space-time codes in an MIMO system is their decoding complexity. Space-time codes achieving full diversity when a fast decoding is used are extremely interesting to high speed wireless communications technologies in both military and commercial applications such as WiFi, WiMax, and 4G systems. Also, space-time coding/modulation achiving full cooperative diversity for cooperative networks with timing errors and frequency offsets will play important roles in making a cooperative network to be practical.

D. **Publications, Abstracts, Technical Reports, and Patent Disclosures or Applications** (during the reporting period):

Refereed Journal Publications Supported by the Grant (Submitted)

50. F. Tian, X.-G. Xia, and P. C. Ching, Signal detection in space-frequency coded cooperative communication system with multiple frequency offsets by exploring code structure, submitted to *IEEE Trans. on Vehicular Technology.*
49. Y. Shang and X.-G. Xia, Shift-Full-Rank Matrices, submitted to *Linear Algebra and Its Applications* (under revision).
48. Y. Shang and X.-G. Xia, Space-time block codes achieving full diversity with linear receivers, submitted to *IEEE Trans. on Information Theory.*
47. X. Guo and X.-G. Xia, An elementary condition for non-norm elements, submitted to *IEEE Trans. on Information Theory.*

Refereed Journal Publications Supported by the Grant (Published and Accepted)

46. H.-M. Wang, X.-G. Xia, and Q. Yin, Computationally Efficient Equalization for Asynchronous Cooperative Communications with Multiple Frequency Offsets, *IEEE Trans. on Wireless Communications*, to appear.
45. Y. Shang and X.-G. Xia, Space-Time Trellis Codes With Asynchronous Full Diversity up to Fractional Symbol Delays, *IEEE Trans. on Wireless Communications*, to appear.
44. J. Xu, G. Li, Y.-N. Peng, X.-G. Xia, and Y.-L. Wang, Parametric velocity synthetic aperture radar: multilook processing and its applications, *IEEE Trans. Geoscience and Remote Sensing*, to appear.
43. J. Xu, G. Li, Y.-N. Peng, X.-G. Xia, and Y.-L. Wang, Parametric velocity synthetic aperture radar: signal modeling and optimal methods, *IEEE Trans. Geoscience and Remote Sensing*, to appear.
42. G. Li, X.-G. Xia, J. Xu, and Y. Peng, A velocity estimation algorithm of moving targets using single antenna SAR, *IEEE Trans. on Aerospace and Electronic Systems*, to appear.

41. G. Li, X.-G. Xia, and Y. Peng, Doppler Keystone Transform: an Approach Suitable for Parallel Implementation of SAR Moving Target Imaging, *IEEE Geoscience and Remote Sensing Letters*, to appear.

40. X.-G. Xia, Channel identification under Doppler and time shifts using mixed training signals, *Journal of Integral Equations and Applications*, Special Issue dedicated to Professor M. Z. Nashed, to appear.

39. Y. Li, W. Zhang, and X.-G. Xia, Distributive High-Rate Space-Frequency Codes Achieving Full Cooperative and Multipath Diversities for Asynchronous Cooperative Communications, *IEEE Trans. on Vehicular Technology*, to appear.

38. Z.-F. Li and X.-G. Xia, Single-Symbol ML Decoding for Orthogonal and Quasi-Orthogonal STBC in Clipped MIMO-OFDM Systems Using A Clipping Noise Model, *IEEE Trans. on Communications*, July 2008, to appear.

37. Zheng Li and X.-G. Xia, An Alamouti Coded OFDM Transmission for Cooperative Systems Robust to Both Timing Errors and Frequency Offsets, *IEEE Trans. on Wireless Communications*, May 2008.

36. X. Guo and X.-G. Xia, Distributed Linear Convolutive Space-Time Codes for Asynchronous Cooperative Communication Networks, *IEEE Trans. on Wireless Communications*, May 2008.

35. X. Guo and X.-G. Xia, A Distributed Space-Time Coding in Asynchronous Wireless Relay Networks, *IEEE Transactions on Wireless Communications*, May 2008.

34. H. Wang and X.-G. Xia, Optimal normalized diversity product of 2 by 2 lattice based diagonal space-time codes from QAM signal constellations, *IEEE Trans. on Information Theory,* April 2008.

33. Z.-F. Li and X.-G. Xia, PAPR Reduction for Repetition Space-Time-Frequency Coded MIMO-OFDM Systems Using Chu Sequences, *IEEE Trans. on Wireless Communications,* April 2008.

32. W. Zhang, Y. Li, X.-G. Xia, P. C. Ching, and K. B. Letaief, Distributed Space-Frequency Coding for Cooperative Diversity in Broadband Wireless Ad Hoc Networks, *IEEE Trans. on Wireless Communications*, March 2008.

31. G. Li, H. Meng, X.-G. Xia, and Y.-N. Peng, Range and Velocity Estimation of Moving Targets Using Multiple Stepped-frequency Pulse Trains, *Sensors*, vol. 8, pp.1343-1350, Feb. 2, 2008. (http://www.mdpi.org/sensors/papers/s8021343.pdf).

30. Y. Shang and X.-G. Xia, Limited-Shift-Full-Rank Matrices With Applications in Asynchronous Cooperative Communications, *IEEE Trans. on Information Theory,* Nov. 2007.

29. W. Zhang, X.-G. Xia, and K. B. Letaief, Space-Time/Frequency Coding for MIMO-OFDM in Next Generation Broadband Wireless Systems, *IEEE Wireless Communications,* Special Issue on Next Generation CDMA vs. OFDMA for 4G Wireless Applications, vol. 14, no. 3, 2007.

28. Z. Li and X.-G. Xia, A Simple Alamouti Space-Time Transmission Scheme for Asynchronous Cooperative Systems, *IEEE Signal Processing Letters*, Nov. 2007.

27. D. Wang, H. Wang, and X.-G. Xia, Space-time trellis code design based on super quasi-orthogonal block codes with minimum decoding complexity, *IEEE Trans. on Communications*, August, 2007.

26. H. Liao and X.-G. Xia, Some Designs of Full Rate Space-Time Codes with Non-Vanishing Determinant, *IEEE Trans. on Information Theory*, August, 2007.

25. G. Li, J. Xu, Y. Peng, and X.-G. Xia, Location and imaging of moving targets using non-uniform linear antenna array, *IEEE Trans. on Aerospace and Electronic Systems*, vol. 43, July 2007.

24. G. Li, J. Xu, Y. N. Peng, and X.-G. Xia, An efficient implementation of a robust phase unwrapping algorithm, *IEEE Signal Processing Letters*, June 2007.

23. W. Zhang, X.-G. Xia, and P. C. Ching, Full-diversity and fast ML decoding properties of general orthogonal space-time block codes for MIMO-OFDM systems, *IEEE Trans. on Wireless Communications*, May 2007.

22. G. Li, J. Xu, Y. Peng, and X.-G. Xia, Moving target location and imaging using dual-speed velocity SAR, *IET Radar, Sonar & Navigation* vol. 1, no. 2, pp.158-163, April 2007.

21. Y. Li and X.-G. Xia, A Family of Distributed Space-Time Trellis Codes with Asynchronous Cooperative Diversity, *IEEE Trans. on Communications*, April 2007.

20. X.-G. Xia and G. Wang, Phase unwrapping and a robust Chinese remainder theorem, *IEEE Signal Process. Letters*, Apr. 2007.

19. H. Zhang, X.-G. Xia, Q. Zhang, and W. Zhu, Iterative decision-aided clipping compensation and its application to scalable video transmission with multi-band OFDM, *IEEE Trans. on Vehicular Technology*, March 2007.

18. H. Liao and X.-G. Xia, A sharpened dynamic range of generalized Chinese theorem for multiple integers, *IEEE Trans. on Information Theory*, Jan. 2007.

17. S. Fu, H. Lou, X.-G. Xia, and J. Garcia-Frias, LDGM coded space-time trellis codes from differential encoding, *IEEE Communications Letters*, Jan. 2007.

16. D. Wang and X.-G. Xia, Space-time trellis code design based on QAM MTCM with trellis shaping, *IEEE Trans. Comm.*, Jan. 2007.

15. W. Zhang, X.-G. Xia, and P. C. Ching, High-rate full-diversity space-time-frequency codes for broadband MIMO block-fading channels, *IEEE Trans. on Communications*, Jan. 2007.

14. W. Zhang, X.-G. Xia, and P.-C. Ching, Clustered pilot tones for carrier frequency offset estimation in OFDM, *IEEE Trans. on Wireless Communications*, Jan. 2007.

13. W. Zhang, X.-G. Xia, and P. C. Ching, Optimal training and pilot pattern design for OFDM systems in Rayleigh fading, *IEEE Trans. Broadcasting*, Dec. 2006.

12. Y. Li and X.-G. Xia, Iterative Demodulation/Decoding Methods Based on Gaussian Approximations for Lattice Based Space-Time Coded Systems, *IEEE Trans. on Wireless Communications*, Aug. 2006.

11. Y. Shang and X.-G. Xia, Shift full rank matrices and applications in space-time trellis codes for relay networks with asynchronous cooperative diversity, *IEEE Trans. on Information Theory*, vol. 52, July, 2006

10. H. Zhang and X.-G. Xia, Iterative Decoding and Demodulation with Soft Interference Cancellation for Single Antenna Vector OFDM Systems, *IEEE Transactions on Vehicular Technology*, July 2006.

9. Q. Wu, Y. Xiong, Q. Zhang, Z. Guo, X.-G. Xia, and Z. Li, Joint Routing and Topology Formation in Multi-hop UWB Networks, *IEEE Journal on Selected Areas of Communications (JSAC)*, Special Issue of UWB Wireless Communications - Theory and Applications, April 2006.

8. K. Lu, S. Fu, and X.-G. Xia, Closed form designs of complex orthogonal space-time block codes of rates (k+1)/(2k) for 2k-1 or 2k transmit antennas, *IEEE Trans. on Information Theory*, vol. 51, Dec. 2005.

7. G. Wang, X.-G. Xia, and V. C. Chen, Dual-speed SAR imaging of moving targets, *IEEE Trans. on Aerospace and Electronics Systems*, Jan. 2006.

6. Y. Wu, X.-G. Xia, Q. Zhang, W. W. Zhu, and Y.-Q. Zhang, Collision Probability and Throughput Analysis in a DS-CDMA Wireless Network, *IEEE Trans. on Vehicular Technology*, Jan. 2006.

5. X.-G. Xia and K. Liu, A generalized Chinese remainder theorem for residue sets with errors and its application in frequency determination from multiple sensors with low sampling rates, *IEEE Signal Processing Letters*, Nov. 2005.

4. Q. Wu, Y. Xiong, H. Wu, Z. Guo, Q. Zhang, X.-G. Xia, and Z. Li, Performance evaluation of the beacon period contraction algorithm in UWB MBOA MAC, *IEEE Communications Letters*, Oct. 2005.

3. D. Wang and X.-G. Xia, Super orthogonal differential space-time trellis coding and decoding, *IEEE Journal on Selected Areas in Communications*, Sept. 2005.

2. D. Wang, G. Wang, and X.-G. Xia, An Orthogonal Space-Time Coded Partial Response CPM System with Fast Decoding for Two Transmit Antennas, *IEEE Trans. on Wireless Communications,* Sept. 2005.

1. H. Zhang, X.-G. Xia, L. Cimini, and P. C. Ching, Synchronization Techniques and Guard Band Configuration Scheme for Single-Antenna Vector OFDM Systems, *IEEE Trans. on Wireless Communications,* Sept. 2005.

Published Conference Proceeding Publications

43. X. Guo and X.-G. Xia, On Full Diversity for Linear Dispersion Codes with Partial Interference Cancellation Group Decoding, International Symp. on Information Theory (ISIT), Toronto, July 6-11 2008.

42. H.-M. Wang, X.-G. Xia, Q. Yin and W. Wang, Computationally Efficient MMSE and MMSE-DFE Equalizations for Asynchronous Cooperative Communications with Multiple Frequency Offsets International Symp. on Information Theory (ISIT), Toronto, July 6-11 2008.

41. Y. Shang and X.-G. Xia, An Improved Fast Recursive Algorithm for V-BLAST With Optimal Ordered Detections, Intern. Conf. Communications (ICC), Beijing, China, May 2008.

40. F. Tian, X.-G. Xia, and P. C. Ching, Signal Detection in a Cooperative Communication System with Multiple CFOs by Exploiting the Properties of Space-Frequency Codes, Intern. Conf. Communications (ICC), Beijing, China, May 2008.

39. X. Guo and X.-G. Xia, Distributed Linear Convolutive Space-Time Codes for Asynchronous Cooperative Communication Networks, Intern. Conf. Communications (ICC), Beijing, China, May 2008.
38. X. Guo and X.-G. Xia, Distributed linear space-time convolutional codes achieving asynchronous full cooperative diversity with MMSE-DFE receivers, IEEE Wireless Communications and Networking Conference, Las Vegas, April, 2008.
37. F. Tian, X.-G. Xia, and P. C. Ching, A Simple ICI Migigation method for a space-frequency coded cooperative communication system with mutilple CFOs, Intern. Conf. Acoustics, Speech and Signal Process., Las Vegas, April, 2008.
36. Z. Li and X.-G. Xia, PAPR reduction for space-time-frequency coded MIMO-OFDM systems, the IEEE Globecom 2007, Washington D.C., Nov. 2007.
35. Z. Li and X.-G. Xia, Fast ML decoding for OSTFBC and QOSTFBC coded MIMO-OFDM system with clipping, the IEEE Globecom 2007, Washington D.C., Nov. 2007.
34. Y. Shang and X.-G. Xia, Limited-Shift-Full-Rank Matrices With Applications in Asynchronous Cooperative Communications, the IEEE Globecom 2007, Washington D.C., Nov. 2007.
33. Y. Shang and X.-G. Xia, Overlapped Alamouti Codes, the IEEE Globecom 2007, Washington D.C., Nov. 2007.
32. Z. Li and X.-G. Xia, An Alamouti coded cooperative transmission robust to both timing errors and frequency offsets, The 2nd International Workshop on Advances in Wireless Sensor Networks (IWASN) 2007, Philadelphia, PA, Aug. 6, 2007.
31. Z. Li and X.-G. Xia, Clipping noise model based fast ML decoding for OSTBC and QOSTBC in clipped MIMO-OFDM systems, International Symp. on Information Theory (ISIT), Nice, France, June 25-30 2007.
30. Y. Shang and X.-G. Xia, A criterion and design for space-time block codes achieving full diversity with linear receivers, International Symp. on Information Theory (ISIT), Nice, France, June 25-30 2007.
29. X. Guo and X.-G. Xia, An Elementary Condition for non-norm elements for QAM and HEX signals, International Symp. on Information Theory (ISIT), Nice, France, June 25-30 2007.
28. W. Zhang, Y. Li, X.-G. Xia, P. C. Ching, and K. B. Letaief, Distributed space-frequency coding in broadband ad hoc networks, International Conf. on Acousitcs,

Speech and Signal Process. (ICASSP), Honolulu, Hawaii, April 15-20, 2007.

27. J. Xu, G. Li, Y.-N. Peng, and X.-G. Xia, Adaptive detection of ground moving target based on velocity synthetic aperture radar, IEEE Radar Conference, Waltham, MA, USA, April 17-20, 2007.

26. F. Tian, X.-G. Xia, and P. C. Ching, Signal Detection for Space-Frequency Coded Cooperative Communication System with Multiple Carrier Frequency Offsets, IEEE Wireless Communications and Networking Conference, Hong Kong, March 2007.

25. D. Wang, J. Zhang, A. Molisch, N. B. Mehta, and X.-G. Xia, Non-Unitary Super Orthogonal Differential Space-Time Trellis Coding and Decoding, IEEE Wireless Communications and Networking Conference, Hong Kong, March 2007.

24. X. Guo and X.-G. Xia, A simple construction of nonvanishing determinant space-time block codes based on cyclic division algebra, Proc. Information Theory and Application (ITA) Workshop, University of California at San Diego, La Jolla, California, Jan. 29-Feb. 2, 2007 (Invited).

23. W. Zhang, K. B. Letaief, X.-G. Xia, W. Zhu, and M. Wu, Advances in Space-Time/Frequency Coding for Next Generation Broadband Wireless Communications, IEEE Radio and Wireless Symp., Long Beach, CA, USA, Jan. 9-11, 2007.

22. Y. Li, W. Zhang, and X.-G. Xia, Distributive High-Rate Space-Frequency Codes Achieving Full Cooperative and Multipath Diversities for Asynchronous Cooperative Communications, Proc. of Globecom 2006, San Francisco, Nov. 2006.

21. Y. Shang and X.-G. Xia, Space-time trellis codes with asynchronous full diversity up to fractional symbol delays, Proc. of Globecom 2006, San Francisco, Nov. 2006.

20. S. Fu, H. Wang, and X.-G. Xia, New recursive space-time codes from general differential encoding, Proc. Information Theory Workshop, Chengdu, China, Oct. 22-26, 2006 (invited).

19. Y. Li, W. Zhang, and X.-G. Xia, Distributive High-Rate Full-Diversity Space-Frequency Codes for Asynchronous Cooperative Communications, Proc. of ISIT 2006, Seattle, USA, July 9-14, 2006.

18. Y. Shang and X.-G. Xia, Shift Full Rank Matrices with Applications in Asynchronous Cooperative Communications, Proc. of ISIT 2006, Seattle, USA, July 9-14, 2006.

17. Y. Shang and X.-G. Xia, Some Diversity Product Properties of A Family of Space-Time Trellis Codes with Asynchronous Full Diversity, Proc. of CISS 2006, Princeton University, March 2006.
16. W. Zhang, X.-G. Xia, and P. C. Ching, Design of Orthogonal Space-Time Block Codes for MIMO-OFDM Systems with Full Diversity and Fast ML Decoding, Proc. of ICASSP 2006, Toulouse, France, May 14-19, 2006.
15. Y. Li, Y. Shang, and X.-G. Xia, A Family of Distributed Space-Time Trellis Codes Achieving Full Diversity for Asynchronous Cooperative Communications, Proc. Information Theory and Application – Inaugural Workshop, University of California at San Diego, La Jolla, California, Feb. 6-10, 2006 (Invited).
14. D. Wang, H. Wang, and X.-G. Xia, Space-Time Trellis Code Design Based on Super QOSTBC with Minimum Decoding Complexity, Proc. of Globecom 2005, St. Louis, MO, USA, Nov. 28-Dec.2, 2005.
13. W. Zhang, X.-G. Xia, and P. C. Ching, High-Rate Full-Diversity Space-Time-Frequency Codes for MIMO Multipath Block-Fading Channels, Proc. of Globecom 2005, St. Louis, MO, USA, Nov. 28-Dec.2, 2005.
12. S. Fu, X.-G. Xia, and H. Wang, Recursive Space-Time Trellis Codes Using Differential Encoding, Proc. of Globecom 2005, St. Louis, MO, USA, Nov. 28-Dec.2, 2005.
11. W. Zhang, X.-G. Xia, and P. C. Ching, Universal space-frequency block coding for MIMO-OFDM system, Proc. of 2005 Asia-Pacific Conf. Communications, Perth, Western Australia, Oct. 3-5, 2005.
10. Y. Li and X.-G. Xia, Full Diversity Distributed Space-Time Trellis Codes for Asynchronous Cooperative Communications, Proc. ISIT 2005, Adelaide, Australia, Sept. 4-9, 2005.
9. Y. Liao, H. Wang, and X.-G. Xia, Some lattice based diagonal and full rate space-time block codes, Proc. ISIT 2005, Adelaide, Australia, Sept. 4-9, 2005.
8. H. Wang, D. Wang, and X.-G. Xia, On optimal quasi-orthogonal space-time block codes with minimum decoding complexity, Proc. ISIT 2005, Adelaide, Australia, Sept. 4-9, 2005.
7. S. Fu, X.-G. Xia, and H. Wang, A recursive space-time trellis codes from differential encoding, Proc. the 15th Virginia Tech. Symp. on Wireless Personal Communications, Virginia Tech., VA, June 8-10, 2005.

6. W. Zhang, X.-G. Xia, and P. C. Ching, Achieving high-diversity in MB-OFDM systems, Proc. of the WirelessCom 2005, Hawaii, USA, June 13-16, 2005.
5. W. Zhang, X.-G. Xia, and P. C. Ching, Rate two full-diversity space-frequency code design for MIMO-OFDM, Proc. of The Sixth IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), New York, June, 2005.
4. D. Wang, H. Wang, and X.-G. Xia, Space-Time Trellis Code Design Based on Super QOSTBC with Minimum Decoding Complexity, Proc. of The Sixth IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), New York, June, 2005.
3. D. Wang and X.-G. Xia, Super Orthogonal Differential Space-Time Trellis Coding and Decoding, Proc. ICASSP 2005, Philadelphia, March 18-23, 2005.
2. Y. Li and X.-G. Xia, Iterative Channel Estimation for Impulse Radio Ultra-Wide Band Communication Systems, Proc. ICASSP 2005, Philadelphia, March 18-23, 2005.
1. Y. Li and X.-G. Xia, A Family of Distributed Space-Time Trellis Codes with Asynchronous Cooperative Diversity, Proc. of The Fourth International Conference on Information Processing in Sensor Networks, UCLA, Los Angeles, CA. April 25-27, 2005.

F. Collaborators:

W. Zhang, Q. Zhang, K. B. Letaief, Hong Kong University of Science and Technology, W. K. Ma, P. C. Ching, the Chinese University of Hong Kong, G. Li, J. Xu, Y. N. Peng, Tsinghua University, Q. Yin, W. Wang, Xi'an Jiao Tong University, J. Garcia-Frias, Len Cimini, University of Delaware, G. Wang, Navini Inc., W. Zhu, Intel

G. Post-doctors, Students Supported and Partially Supported by the Grant

Ph.D. Students Supported by the Grant: Yue Shang, Xiaoyong Guo, Zhefeng Li